Remote Sensing of the Aerosol Optical Thickness from SeaWiFS in Comparison with the in situ Measurements

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ABSTRACT

We describe a matchup procedure which compares the retrieved SeaWiFS aerosol optical thicknesses with data from ground in situ measurements. The aerosol optical thickness at 865 nm is a by-product of the SeaWiFS atmospheric correction and is routinely retrieved from SeaWiFS measurements. This work is part of the SeaWiFS calibration and validation efforts in studying the aerosol optical properties over the ocean, thereby validating aerosol models used in the atmospheric correction in the ocean color sensors. The aerosol model is an integral part of the SeaWiFS atmospheric correction. We describe the SeaWiFS aerosol retrieval algorithm, the data acquisitions from both SeaWiFS and in situ measurements, and the matchup procedure. Finally, we present and discuss some *preliminary* comparison results.

1. Introduction

Aerosols play an important role in climate forcing and biogeochemical cycling (Charlson et al., 1992). They not only directly influence radiative transfer in the atmosphere and hence change the radiance reflected to space, but also indirectly affect the radiation budget by providing cloud condensation nucleii that lead to cloud formation (Charlson et al., 1987). There have been continuous efforts in recent years with both ground in situ measurements and remote retrieval of aerosol optical properties using aircraft and/or satellite sensors. The primary goals of NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (Hooker et al., 1992) are routine global ocean color measurements and ocean bio-optical property data. However, in retrieving the ocean near-surface signals from sensor-measured radiances at the satellite altitude, the atmospheric effects must be removed. The SeaWiFS atmospheric correction algorithm uses two near-infrared bands (765 and 865 nm) to estimate the aerosol optical properties and extrapolate these into the visible (Gordon and Wang, 1994). Therefore, the aerosol optical properties, in particular, aerosol optical thickness (AOT), are by-products of the SeaWiFS atmospheric correction. The aerosol optical thickness at 865 nm, $t_a(865)$, is routinely retrieved from SeaWiFS measurements. In this paper, we outline our efforts in comparing and validating the SeaWiFS aerosol optical products with the in situ measurements mainly from the data of the Aerosol Robotic Network (AERONET) (Holben et al., 1998). Some other in situ measurements from field campaigns within the NASA Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) project are also analyzed. There are two primary objectives behind these comparisons. First, since the AOT at 865 nm $t_a(865)$ is part of the SeaWiFS standard product suite, it warrants validation. The second objective of this work is to determine the validity of the suite of aerosol models currently used by SeaWiFS for atmospheric correction.

2. Procedures

In this section, we first briefly describe the SeaWiFS aerosol optical thickness retrieval algorithm. We then extend the algorithm to retrieve the aerosol optical thicknesses in all the SeaWiFS bands. Next, we outline the data acquisition procedure and matchup criteria for both SeaWiFS and in situ observations. Finally, we discuss a data analysis strategy for both SeaWiFS and in situ measurements.

2.1 The SeaWiFS Aerosol Retrieval Algorithm

The upward reflectance at the top of the ocean-atmosphere system, measured at the SeaWiFS two NIR bands (765 and 865 nm) can be written as:

$$r_t(l) = r_r(l) + r_a(l) + r_{ra}(l), \qquad (1)$$

where the three terms are contributions from multiple scattering of air molecules (Rayleigh scattering), aerosols, and Rayleigh-aerosol interactions, respectively. Note that the surface sun glitter and whitecap terms in the above equation have been ignored. The value of the $r_a(l) + r_{ra}(l)$ in Eq. (1) can be estimated from the sensor-measured radiance $r_t(l)$ and the computed Rayleigh scattering reflectance $r_r(l)$. By using a set of candidate aerosol models developed by *Shettle and Fenn* (1979), the effects of the spectral variation of the $r_a(l)+r_{ra}(l)$ at the two NIR bands are then extrapolated into the visible bands (Gordon and Wang, 1994). The extrapolation was achieved through a process of aerosol model selection from evaluation of the atmospheric-correction parameter, $e(l_i, l_j)$, defined as (Gordon and Wang, 1994; Wang and Gordon, 1994)

$$e(l_i, l_j) = r_{as}(l_i) / r_{as}(l_j), \qquad (2)$$

where $r_{as}(l_j)$ is the single scattering aerosol reflectance. For a given solar and viewing geometry, parameter $e(l_i, l_j)$ depends only on the aerosol model. Therefore, it forms the link between $e(l_i, l_j)$ and the aerosol model.

Using aerosol lookup tables, the $r_a(l)+r_{ra}(l)$ values at the SeaWiFS two NIR bands can be converted to the single scattering reflectance $r_{as}(l)$, thereby providing $e(765,865)$ values for given aerosol models. The SeaWiFS retrieved parameter, $e^{(ave)}$, was obtained by a weighted-averaging over individual e values derived from a set of aerosol models. Two aerosol models with $e^{(1)}$ and $e^{(2)}$ such that

$$e^{(1)} < e^{(ave)} < e^{(2)} \qquad (3)$$

can be obtained, where $e^{(1)}$ is for the model with the largest e value < $e^{(ave)}$, and $e^{(2)}$ is for the model with the smallest e value > $e^{(ave)}$. With the retrieved two aerosol models, the corresponding aerosol optical thicknesses for a given wavelength λ, $t_a^{(1)}(l)$ and $t_a^{(2)}(l)$, can then be estimated. Finally, the SeaWiFS aerosol optical thickness are obtained by interpolating between the two models as

$$t_a(l) = (1-r_a)t_a^{(1)}(l) + r_a t_a^{(2)}(l), \text{ and } \quad r_a = \frac{e^{(ave)} - e^{(1)}}{e^{(2)} - e^{(1)}} \qquad (4)$$

is the interpolation ratio between the two models.

SeaWiFS routinely yields the AOT at the wavelength 865 nm as a standard product. However, it is straightforward to extend the current AOT retrievals to the remaining SeaWiFS wavelengths using Eq. (4). After making a necessary interpolation for a slight shift from the SeaWiFS bands, comparisons between SeaWiFS AOT and ground measurements are possible. Both the Cimel sun/sky scanning radiometer and MicroTops II sunphotometer have spectral wavelengths at 440, 500, 670, and 870 nm corresponding to the SeaWiFS bands 2 (443 nm), 4 (510 nm), 6 (670 nm), and 8 (865 nm).

2.2 The In Situ Data Acquisition

The ground based measurements utilized for the AOT matchup analyses come from two primary sources: automated Cimel sun/sky scanning radiometer managed as part of the AERONET network, and hand-held MicroTops II sunphotometers. A select group of the ground stations from the AERONET were chosen. These instruments were located at either coastal or island stations and were operational for a reasonable length of time after SeaWiFS went into operation. Table 1 provides some of the AERONET station name, location (latitude and longitude), and corresponding responsible AERONET principle investigator (PI). We are current underway to include additional AERONET stations.

The hand-held MicroTops II sunphotometer data, on the other hand, were collected by various investigators in field campaigns associated with the SIMBIOS project. Data from the MicroTops instruments are reprocessed from raw voltages using code adapted from the AERONET standard Cimel processing code. This ensures that

Table 1. AERONET sites utilized for the aerosol matchup analyses.

AERONET Station	Latitude	Longitude	AERONET PI
Bahrain	26.32	50.50	Charles McClain†
Bermuda	32.37	-64.70	Brent Holben
Dry Tortugas	24.60	-82.80	Ken Voss/Howard Gordon
Kaashidhoo	4.97	73.47	Brent Holben
Lanai	20.83	-156.99	Charles McClain†
Rame Head (PlyMBODY)	50.37	-4.15	Gerald Moore
San Nicolas Island	33.26	-119.49	Robert Frouin

†SIMBIOS Project Office.

the AOT data derived from the MicroTops measurements will be comparable to the data provided by the AERONET.

For the matchup purpose, the ground based measurements were reduced to include only those records that fall ±1 hour of the SeaWiFS overpass for a given station. These include the aerosol optical thicknesses measured at the four spectral wavelengths (440, 500, 670, and 870 nm). As an initial quality control step, the data were further reduced to include only those records that had reasonable values of AOT at these four bands, i.e., if there was a missing record in any one of these four bands, the data records were discarded. Additional quality control of the in situ data is necessary to eliminate cloud contaminated data. The AERONET has a quality assured (cloud-screened) database, however, this data set is extremely limited, much of it does not encompass the SeaWiFS ±1 hour matchup criteria. Therefore, much of data we are using in this report have not gone through the AERONET quality assurance. It is our intention to use the AERONET quality assured data when possible at a later time.

2.3 The SeaWiFS Data Acquisition

The SeaWiFS AOT data were obtained by spatially co-locating a 5×5 pixel grid box around the pixel containing the ground-base measurement station, thereby providing a maximum 25 SeaWiFS retrievals in each matchup. The SeaWiFS operational code was modified to output, at a pixel by pixel level, the AOT at wavelength 865 nm, retrieved two aerosol models, as well as the model partition ratio r_a value. Therefore, aerosol optical thicknesses at all the SeaWiFS wavelengths can be calculated using Eq. (4).

2.4 Data Analyses

As discussed in the above, the SeaWiFS data were obtained by a distance-weighted averaging over a 5×5 pixel grid box spatially, whereas the AOT data from the Cimel measurements were derived by a time-weighted averaging during the SeaWiFS overpass (±1 hour). Usually, the Cimel instruments routinely take one measurement every 15 minutes near local noon. Therefore, for a given SeaWiFS file there may be as many as eight AERONET measurements that qualify as a match for the 2-hour time window. The number of hand-held MicroTops II measurements that match a given SeaWiFS file, however, varies greatly since the measurement protocol for these instruments is not yet well defined. In general, there should be a minimum of three MicroTops measurements per matched SeaWiFS file. The ground-based measurements are averaged after weighting by the time difference between the in situ measurement and the SeaWiFS overpass. Since each match may have up to 25 valid SeaWiFS pixels, the valid pixels for each match are averaged using the distance-weighted from the center pixel. Once averaged, the ground based measurements are compared with the SeaWiFS derived values on a band by band basis for each ground station.

3. Preliminary Results

We compared the SeaWiFS derived aerosol optical thicknesses with those from the ground in situ measurements. As this is an ongoing research project, all results shown in here are *preliminary*. Figs. 1(a) and 1(b) provide examples of an overall comparison results of $t_a(l)$ between SeaWiFS and Cimel measurements at two wavelengths 440 and 865 nm. The Cimel measurements were from the AERONET stations listed in Table 1.

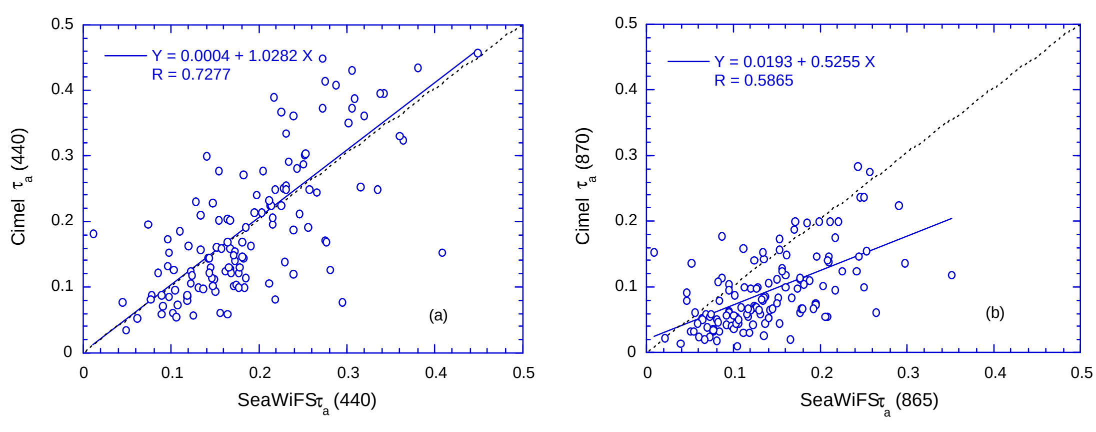

Figure 1. The retrieved SeaWiFS AOTs compared with the ground in situ measurements from the AERONET for the wavelength of (a) 440 nm and (b) 865 nm (870 nm for Cimel data).

Table 2. Three samples of MicroTops II data compared with SeaWiFS.

λ (nm)	Aerosol Optical Thickness $t_a(l)$								
	Sea of Cortez (Jason Project) Investigator: G. Feldman			Gulf of California Investigator: J. Mueller			Massachusetts Bay B. Schieber & A. Subramaniam		
	SeaWiFS	MicroTops	Diff (%)	SeaWiFS	MicroTops	Diff (%)	SeaWiFS	MicroTops	Diff (%)
440	0.0555	0.0730	-24.0	0.1635	0.1884	-13.2	0.1775	0.1936	-8.3
500	0.0509	0.0553	-8.0	0.1469	0.1504	-2.3	0.1538	0.1703	-9.7
670	0.0395	0.0446	-11.4	0.1076	0.0911	18.1	0.1013	0.1099	-7.8
865	0.0304	0.0334	-9.0	0.0774	0.0954	-18.9	0.0641	0.0758	-15.4

The number of data contributed to each plot in Fig. 1 from individual station is, from the top list to the bottom in Table 1, 20, 10, 55, 19, 4, 5, and 17. Therefore, the station of Lanai only contributed 4 points, whereas Dry Tortugas has 55 data in each plot in Fig. 1. The dotted lines in Figs. 1(a) and 1(b) are the 1:1 line, while the solid lines are the linear least-square fit to the data. The captions within each plot give the slope and intercept of the linear fit along with the correlation coefficient for that fit. Though the comparison results vary both in time and location, it appears that SeaWiFS has tendency of overestimating $t_a(l)$ with respect to the in situ measurements. This is most evident with the SeaWiFS 865 nm comparison results. Note that, since the SeaWiFS band 8 has not been absolutely calibrated on orbit, any error in calibration may contribute to the error in the $t_a(865)$ evaluations. Also, any calibration error in the SeaWiFS band 7 leads to the algorithm selecting wrong aerosol model, which causes error in the AOT computations. On the other hand, some in situ data are suspected to be erroneous due to instrument calibration. Obviously, more studies are needed to understand all of these. We want to emphasize that all results are *preliminary*.

Similarly, the in situ MicroTops II data, which were from the various SIMBIOS calibration and validation campaigns, have been compared with the SeaWiFS measurements. Although this work is still in the initial phase, some results are promising. Table 2 shows three sample comparison results from three field experiments. In these three examples, the SeaWiFS results were almost all underestimated as compared with the MicroTops II measurements, though the three results are usually agreed reasonably well.

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References

Charlson, R.J., Lovelock, J.E., Andreae, M.O., and Warren, S.G. (1987), Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate, *Nature*, 326: 655-661.

Charlson, R.J., Schwartz, S.E., Hales, J.M., Cess, R.D., Coakley, J.A., Hansen, J.E., and Hofmann, D.J. (1992), Climate forcing by anthropogenic aerosols, *Science*, 255: 423-430.

Gordon, H.R., and Wang, M. (1994), Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: A preliminary algorithm, *Appl. Opt.*, 33: 443-452.

Holben, B.N., Eck, T.F., Slutsker, I., Tanre, D., Buis, J.P., Setzer, A., Vermote, A., Reagan, J.A., Kaufman, Y., Nakajima, T., Lavenu, F., Jankowiak, I., and Smirnov, A. (1998), AERONET-Afederated instrument network and data archive for aerosol characterization, *Rem. Sens. Environ.*, 66: 1-16.

Hooker, S.B., Esaias, W.E., Feldman, G.C., Gregg, W.W., and McClain, C.R., An Overview of SeaWiFS and Ocean Color, NASA Goddard Space Flight Center, Greenbelt, MD, 1992.

Shettle, E.P., and Fenn, R.W., Models for the Aerosols of the Lower Atmosphere and the Effects of Humidity Variations on Their Optical Properties, U.S. Air Force Geophysics Laboratory, Hanscom Air Force Base, Mass., 1979.

Wang, M., and Gordon, H.R. (1994), A simple, moderately accurate, atmospheric correction algorithm for SeaWiFS, *Rem. Sens. Environ.*, 50: 231-239.